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(54) Title: APPARATUS AND METHOD FOR COMPENSATION OF CHROMATIC DISPERSION IN OPTICAL FIBERS

(57) Abstract

A dispersion compensation device uses at least two chromatic dispersion compensation fibers to compensate for chromatic dispersion present in an optical communication system. Two dispersion orders can be corrected using appropriate lengths of two serially coupled compensation fibers having different dispersion characteristics. The device can compensate for N additional orders of dispersion by using N additional compensation fibers with unique dispersion characteristics. The device can be coupled directly to a transmission fiber.

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APPARATUS AND METHOD FOR COMPENSATION OF CHROMATIC DISPERSION IN OPTICAL FIBERS

Cross-Reference to Related Applications

This application claims priority to provisional U.S. patent application number 60/079,423 which was filed March 26, 1998, provisional U.S. patent application number 60/089,350 which was filed June 15, 1998 and provisional U.S. patent application number 60/091,026 which was filed June 29, 1998 and incorporates by reference U.S. patent applications "Transverse Spatial Mode Transformer for Optical Communication" (attorney docket no. LCM-001) and "Optical Communication System with Chromatic Dispersion Compensation" (attorney docket no. LCM-002) filed concurrently herewith.

Field of the Invention

The invention relates to fiber optic telecommunication systems and more specifically to chromatic dispersion compensation in such systems.

Background of the Invention

The tendency of a pulse of light propagating through an optical fiber to broaden is a result of the fact that different wavelengths of light pass through the fiber at different speeds. This speed differential which causes the pulse to broaden is termed chromatic dispersion. Chromatic dispersion presents a problem in modern optical communication systems because the tendency of light pulses to broaden as they propagate down the fiber causes the closely spaced light pulses to overlap in time. This overlap can have an undesirable effect since it restricts how closely spaced the pulses can be. This in turn limits the data bandwidth of the optical fiber.

There are many characteristics of dispersion. First order dispersion is the rate of change of index of refraction with respect to wavelength in the fiber. First order dispersion is also referred to as group velocity. Second order dispersion is the rate of change of the first order dispersion with respect to wavelength. Second order dispersion produces the pulse broadening. Third order dispersion is the rate of change of broadening with respect to a change in wavelength. This is often referred to as the dispersion slope.

Several solutions have been proposed to mitigate the effects of dispersion in transmission fibers. One technique involves the use of a compensating optical fiber having an appropriate

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length and which has a dispersion that is opposite to the dispersion characteristic of the transmission fiber. The result is dispersion in the transmission fiber is substantially matched and canceled by the total dispersion in the compensating fiber. While this technique offers a solution to the dispersion problem, it may be impractical in actual use because of the attenuation due to the required length of the compensating fiber. In such a case, the total transmission length of the fiber is significantly increased thereby increasing the signal attenuation in the fiber. Furthermore, it may be difficult to find a fiber of the desired length with the required dispersion properties.

It is also difficult to design a fiber having a changing index of refraction across the diameter of the fiber (the fiber index profile) that will compensate simultaneously for the second and third dispersion orders. It is even more difficult to control the material properties of such fibers even in the most accurate fabrication process necessary to produce such fibers. In addition, the process of fabricating the single compensating chromatic dispersion fiber is expensive and generally not practical.

When a pulse of light is transmitted through an optical fiber, the energy follows a number of paths which cross the fiber axis at different angles. A group of paths which cross the axis at the same angle is known as a mode. Sometimes it is necessary to limit or control the number of modes used in a transmission system. The fundamental mode LP_{01} in which light passes substantially along the fiber axis is often used in high bandwidth transmission systems using optical fibers commonly referred to as single mode fibers.

The dispersion properties of high order modes have been investigated at length. There is a dependence of high order mode dispersion on wavelength and on the properties of the fiber. By properly designing the fiber index profile it is possible to make the dispersion slope be positive, negative or zero. It is also possible to make the magnitude of the dispersion be negative, zero or slightly positive. Using these two properties one can either control or compensate for the dispersion in any transmission fiber.

Systems have been developed to take advantage of higher order modes to compensate for dispersion in a typical optical communication system. In such systems it has been necessary to first convert the lower order fundamental mode of the light to a higher order spatial mode. This is accomplished using longitudinal mode conversion.

Conventional methods for longitudinal mode conversion are based on introducing a periodic perturbation along the fiber axis. The length of each period and the number of periods in

these longitudinal converters must be determined accurately according to the wavelength, the strength of the perturbation, and the modes involved. By constructing a longitudinal mode converter it is possible to achieve good efficiency in transferring the energy from one mode to the other in a limited spectral bandwidth. This spectral property has been used in Dense Wavelength Division Multiplexing (DWDM) applications in telecommunications for other applications. Unfortunately, this technique is accompanied by significant energy attenuation and it cannot be used over broad spectral bandwidths.

Another deficiency associated with longitudinal mode converters is related to the fact that after the conversion, only a single mode should be present in the fiber. It can be difficult to discriminate between desired modes and undesired modes having almost the same group velocities because unwanted modes can appear at the output of the converter. As the modes propagate, modal dispersion occurs and the pulse broadens. Generally, longitudinal mode converters introduce significant energy attenuation and noise. Therefore, a trade-off must be made between having broad-spectrum capability and the demand for converting the original mode to a pure, single, high-order mode.

One such longitudinal mode converter is discussed in patent number 5,802,234. Here, a single mode transmission fiber carries the LP_{01} to a longitudinal mode converter. Before conversion in this system, however, it is necessary to couple the single mode transmission fiber to a multimode fiber while maintaining the signal in the basic LP_{01} mode. This coupling is typically difficult to achieve without signal degradation and any misalignment or manufacturing inaccuracies can result in the presence of higher order modes. It is desirable that only the LP_{01} mode propagate initially in the multimode fiber in order to avoid significant noise that degrades the system performance and typically such coupling results in the propagation of additional modes.

The present invention overcomes the disadvantages of longitudinal mode converters and previous attempts to control dispersion in a fiber optic system.

Summary of the Invention

The present invention relates to an apparatus and method for chromatic dispersion compensation of optical systems. The apparatus and method make use of multiple chromatic dispersion compensation optical fibers. The number of orders of dispersion that can be corrected increases with the number of compensation fibers in the apparatus. Specifically, N orders of

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dispersion can be corrected by serially coupling N chromatic dispersion compensation optical fibers.

In one embodiment, the present invention features a chromatic dispersion compensation module which includes a first and second dispersion compensation fiber. The optical signal is dispersion compensated by each compensation fiber. In one embodiment, one compensation fiber compensates for first order chromatic dispersion and the other compensation fiber compensates for second order chromatic dispersion. In another embodiment, at least one of the compensation fibers is optical coupled to a transmission fiber.

In another aspect, the invention features a method of compensating for chromatic dispersion in an optical system which includes the steps of receiving an optical signal from a transmission fiber, injecting the optical signal into a first compensation fiber and dispersion compensating the optical signal. The method includes the additional steps of injecting the optical signal exiting the first compensation fiber into a second compensation fiber, additionally compensating the optical signal, and injecting the optical signal into a second transmission fiber.

Brief Description of the Drawings

These and other advantages of the invention may be more clearly understood with reference to the specification and the drawings, in which:

FIG. 1 is a block diagram of an embodiment of a typical fiber optic transmission system known to the prior art;

FIG. 2 is a block diagram of an embodiment of the fiber optic transmission system of the present invention including a chromatic dispersion compensation fiber module;

FIG. 3 is a block diagram of an embodiment of the chromatic dispersion compensation fiber module shown in FIG. 2 showing transverse mode transformers and a chromatic dispersion compensation fiber;

FIG. 4 is a block diagram of another embodiment of the chromatic dispersion compensation fiber module of the present invention showing transverse mode transformers and two chromatic dispersion compensation fibers;

FIG. 5 is a highly schematic diagram of an embodiment of a transverse mode transformer shown in FIG. 3;

FIG. 6a is a block diagram of an alternative embodiment of a fiber optic transmission system of the current invention with the leading transmission fiber replaced by a transmission source;

FIG. 6b is a block diagram of an alternative embodiment of a fiber optic transmission system of the current invention with the receiving transmission fiber replaced by a detector;

FIG. 7a is a graph of the intensity as a function of position along the diameter of a fiber in an ideal case;

FIG. 7b is a graph of the intensity as a function of position along the diameter of the fiber after transformation to the LP_{02} mode;

FIG. 8 is a graph of the relative energy in the higher order mode relative to the LP_{01} mode for an element optimized for operation at a wavelength of 1550nm in an ideal case;

FIG. 9 is a block diagram of an alternative embodiment of a transverse mode transformer using two phase elements;

FIG. 10a is a highly schematic diagram of an alternative embodiment of the present invention showing two chromatic dispersion compensation fibers used for multiple order dispersion compensation;

FIG. 10b is a highly schematic diagram of an alternative embodiment of the present invention showing two chromatic dispersion compensation fibers sandwiching a single mode transmission fiber used for multiple order dispersion compensation;

FIG. 11a - 11e are graphs of different solution spaces showing relative design characteristics resulting from the use of first and second order dispersion;

FIG. 12a-12c are illustrations of alternative embodiments of the transverse mode transformer shown embedded in a fiber optic transmission system;

FIG. 13a-13c are graphs of the amplitude versus position plot of the pulse across the diameter of the fiber before, during and after mode transformation;

FIG. 14 is an illustration of an alternative embodiment of the current invention using a polarization beam splitter and a polarization combiner;

FIG. 15 is a schematic diagram of a single bulk component that can be used to replace the discrete bulk optical components in the embodiment shown in FIG. 14;

FIG. 16 shows a representation of the polarization of propagating modes through the element described in FIG. 15;

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FIG. 17 shows a representation of the polarization of propagating modes using a birefringent element;

FIG. 18 is a block diagram of an alternative embodiment of the current invention designed to eliminate the sensitivity of the system to polarization mode dispersion by using a circulator and a Faraday mirror; and

FIG. 19 is a block diagram of an alternative embodiment of the current invention designed to eliminate the sensitivity of the system to polarization mode dispersion without using a circulator.

FIG. 20a-20c are diagrams of alternative embodiments of a transverse mode transformer using internal reflection.

Detailed Description of the Invention

A typical optical fiber transmission system known in the prior art is shown in FIG. 1. Such a system includes a signal transmitter 2 in optical communication with a single mode fiber (SMF) 3 which is in turn in optical communication with a signal receiver 4. (Other components common to optical fiber systems, such as amplifiers, circulators, isolators, etc. are not shown.) A signal is transmitted from the transmitter 2 into the fiber 3 where it propagates some distance. Depending on the length and other properties of the fiber, significant signal attenuation and dispersion can occur in the fiber. The receiver 4 acquires the attenuated signal as it exits the fiber 3.

A basic configuration of the system of the present invention is presented in FIG. 2. A transmitter 2 transmits an optical signal into a communication fiber 3. The communication fiber 3 introduces dispersion that requires compensation. The chromatic dispersion compensation module 10 compensates for signal dispersion introduced by the communication fiber 3 before propagating the signal into a receiver 4.

An embodiment of the chromatic dispersion module 10 is shown in FIG. 3. A signal propagating in a single mode fiber (SMF) 3 enters a mode transformer 28 which converts the basic lower order spatial mode, generally LP_{01}, to a higher order spatial mode, generally LP_{02}, that propagates in a special chromatic dispersion compensating fiber 30. The chromatic dispersion compensation fiber (DCF) 30 is designed to compensate for the first order dispersion of the signal. A second chromatic dispersion compensation fiber 31 with different compensation properties may be coupled to the first chromatic dispersion compensation fiber 30 in order to

compensate for dispersion slope as shown in FIG. 4. If required, more than two chromatic dispersion compensation fibers may be used to compensate even higher order dispersion or alternatively for mode filtering applications. Once compensation is complete, the signal is then converted back to the lower order mode by a second mode transformer 28' and emerges from the chromatic dispersion compensation module 10 in the single mode fiber 3'.

The mode transformer 28 of the present invention is a bi-directional transverse mode transformer. It can be used to convert a lower order spatial mode to a higher order spatial mode. Conversely, the same transverse mode transformer 28 can be used to convert a higher order spatial mode to a lower order spatial mode. Unlike prior mode transformers which used the longitudinal axis of the fiber to accomplish longitudinal mode conversion, the present transverse mode transformer uses transverse properties of the wavefront of the light to mode convert by selectively altering the phase of at least one portion of the wavefront. One embodiment of a transverse mode transformer is shown in FIG. 5. A transverse phase element 58 arranged perpendicular to the longitudinal axis of the fiber is used to accomplish mode transformation. A pulse of light propagates in a single mode fiber 50 with a small diameter core 54. The pulse broadens into an expanded region 56 as it emerges from the fiber. As the pulse passes through the transverse phase element 58 the phase distribution of the pulse is changed. The phase element 58 can consist of a spatially selective phase element which alters the phase of points on the wavefront as a function of their transverse position. A focusing lens 62 focuses the pulse back into the special chromatic dispersion compensation fiber 64, shown as having a broader core 66 simply for explanatory purposes. In many conventional systems the lens 62 is a compound lens. In one embodiment, gradient index (GRIN) lenses are used. The phase element 58 can be any spatially selective phase element, including but not limited to, lenses, mirrors, gratings, electro-optic devices, beamsplitters, reflective elements, graded indexed materials and photolithographic elements.

Phase transformation can be achieved using the properties of spherical aberration inherent in optical lenses. After a wavefront passes through a lens, it will experience spherical aberration. The resulting distorted wavefront can be used with or without a phase element 58 in the transverse mode transformer 28 of the present invention to transform the spatial mode of the original wavefront to a higher order spatial mode.

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FIG. 6a depicts a system in which a transmission source 24 replaces the optical fiber 3 shown in the embodiment in FIG. 4. Here the system does not require an input transmission fiber and retains all the functionality and advantages of the present invention. The transmission source 24 injects an optical signal directly into the chromatic dispersion compensation module 10 where it is pre-compensated before being received by the transmission fiber 3'. Precompensation can be desirable when the transmission fiber 3' has a known dispersion that requires compensation.

FIG. 6b describes a system in which a detector 36 replaces the transmission fiber 3' shown in the embodiment in FIG. 4. Here the system does not require an exit transmission fiber 3' and the functionality of the system is not affected. In this case the optical signal propagates in the optical fiber 3 before being compensated by the chromatic dispersion compensation module 10. Once the signal is down converted by mode transformer 28', it is detected directly by detector 36. This method can conserve energy since there will not be fiber coupling losses exhibited before the detector.

The physical mechanism of the transverse mode transformation presented in this invention is explained with reference to FIGS. 13a to 13c. (FIGS. 13a to 13c share the same horizontal scale.) Figure 13a illustrates the gaussian-like amplitude distribution of mode LP_{01} in a single mode fiber, wherein the horizontal axis represents the transverse position across the diameter of the fiber in arbitrary units and the vertical axis represents the amplitude in arbitrary units. In one embodiment, the transverse phase element 58 (FIG. 5) introduces a step function to the wavefront 20 of the pulse such that the center region 20a of the wavefront 20 is retarded with respect to the outer region 20b of the wavefront 20. Therefore, the inner region 20a and the outer region 20b of the wavefront 20 will differ in phase by 180°. After propagation and transformation, the resulting distribution 22 shown in FIG. 13c enters the chromatic dispersion compensation fiber 64 (see FIG. 5). More than ninety percent of the transverse intensity distribution in the LP_{01} mode (see FIG. 7a) is present in the LP_{02} mode (see FIG. 7b) after transformation. The remaining energy is distributed among higher order modes which are not supported by the special chromatic dispersion compensation fiber 66. Therefore, the fiber will contain substantially a single high order mode (LP_{02}). The same process, but in the reverse order, occurs in the second mode transformer 28' at the opposite end of the compensation fiber 66. This technique can also be applied to convert between other spatial modes.

One of the advantages of this transverse transformation mechanism is its high efficiency over a broad spectrum. FIG. 8 shows the residual energy in the LP_{01} mode for an element optimized for operation at 1550nm. The horizontal axis represents the wavelength of the pulse in nanometers, and the vertical axis represents the ratio between the energy remaining in the low order mode to the total energy of the pulse. Less than one half of a percent of the pulse energy is left in the lowest order mode over greater than 100nm of spectral range.

In order to further improve the transformation efficiency it is possible to use multiple phase elements 74 and 74' as shown in FIG. 9. The pulse emerging from fiber 54 is collimated by lens 72, then it passes through the two phase elements 74 and 74' and is finally focused by lens 72' into a special chromatic dispersion compensation fiber 64. This technique reduces longitudinal sensitivity in the placement of the phase elements. The design of phase elements 74 and 74' can be based on a coordinate transformation technique for converting between spatial modes. The first phase element 74 is designed to have local phase changes across the pulse. Each local phase change redirects (i.e., steers) a small section of the wavefront 20 to a predetermined coordinate on the second phase element 74'. As a result, a predetermined intensity pattern is generated at the second phase element 74'. The second phase element also induces local phase changes across the wavefront so that the resulting wavefront 20 with predetermined intensity and phase distributions at the second element 74' yields the desired spatial mode.

Another embodiment of the chromatic dispersion compensation module 10 of the present invention is shown in FIG. 10a. This embodiment may be used with transverse mode transformers 28, but is not limited to their use. Any means that propagates a pulse with a higher order mode into an optical coupler 6 can use the invention. After the higher order pulse passes through optical coupler 6, the pulse then enters the first chromatic dispersion compensation fiber (DCF_1) 8 which is designed to compensate for the dispersion of the communication fiber 3. DCF_1 8 is spliced to a second dispersion compensation fiber (DCF_2) 10 through a splice 12. DCF_2 10 is designed to have minimal second order dispersion at the point where the dispersion slope is maximum. By properly choosing the design parameters, a minimal length of DCF 8 and 10 is required to compensate for dispersion. DCF_1 8 and DCF_2 10 can be designed to operate with the basic LP_{01} mode as long as they have different dispersion characteristics. The order in which DCF_1 8 and DCF_2 10 are arranged can be changed. Generally, more chromatic dispersion compensation fibers are required as the number of dispersion orders to be compensated increases.

The chromatic dispersion compensated pulse passes into the outgoing optical transmission fiber 3' at splice 14. FIG. 10b illustrates another embodiment of the invention. A single mode fiber is sandwiched between two dispersion compensation fibers. Any number of combinations can be realized without detracting from the essence of the invention.

Graphs of possible solutions using the chromatic dispersion compensation fibers of the present invention are shown in FIGS. 11a-11e. The horizontal axes represent the second order dispersion, and the vertical axes represent the second order dispersion slope (i.e., third order dispersion). The dispersion compensation introduced by the chromatic dispersion compensation fibers is presented as arrow 24. FIG. 11a represents an ideal system, where the desired dispersion solution is presented as the point 20. By choosing the proper length of chromatic dispersion compensation fiber, the desired results are achieved. Unfortunately, in conventional communication systems it is difficult to change the relationship between the dispersion orders. Moreover, it is difficult to even predict this relationship before fabrication of the compensation fiber is completed. In addition, this relationship varies strongly according to fabrication processes. Therefore, if the desired amount of dispersion compensation presented at point 20 is displaced as illustrated in FIG. 11b, it is impossible to achieve the desired compensation. It is possible, however, to increase the length of the DCF in order to add length 26 to the arrow 24, so that the actual magnitude of dispersion is increased and the resulting dispersion 27 will approximate the desired dispersion 20.

By combining two or more different fibers it is possible to achieve a variety of dispersion properties. The dispersion properties of DCF_1 8 and DCF_2 10 in FIG. 10 are represented as 32 and 34 in FIG. 11c. The area 36 represents the solution space of dispersion compensation which can be achieved by proper combination of the two fibers 8 and 10.

FIG. 11d represents an example of such a combination. Using a combination of two or more DCFs, one can compensate for higher orders of dispersion. In order to achieve better coverage of the dispersion possibilities it is desirable to increase the angle between the arrows 32 and 34 in FIG. 11c. It is difficult to achieve this result by using conventional single mode DCFs, however, high order mode-dispersion compensation fibers (HOM-DCF) can achieve more than 90 degrees difference between two different DCFs as presented in FIG. 11e. This system is insensitive to the exact properties of the DCFs, because changing the length of the fibers can compensate for any deviation in the result.

FIG. 12a depicts an alternative embodiment of the transverse mode transformer of the present invention and shows a connection, between two fibers, designed to modify the wavefront. Both fibers include a core 10 and cladding 12. The face of the transmission fiber 14 can be perpendicular to the face of the dispersion compensation fiber 6 or at a small angle to the DCF 6 in order to eliminate reflection noise. The end face of at least one of the fibers has a predetermined binary pattern 16. The pattern 16 can be etched onto the fiber or be in optical communication with the fiber. The pattern is designed to redistribute a gaussian wavefront such as that corresponding to the LP_{02} mode as described in FIG. 7b. In order to achieve an instantaneous change of the wavefront, the height of the binary pattern is set in one embodiment to 1.5 microns. This height is much smaller than the 'Rayleigh range', which is approximately 50 microns in a conventional fiber. The Rayleigh range is defined as $\pi r^2/\lambda$ where r is the radius of the wavefront and λ is the wavelength of the light.

FIG. 12b depicts an embodiment in which the fibers 4, 6 are in contact with each other in order to reduce the relative motion and losses. FIG. 12c depicts the same architecture as in FIG. 12b except that a transparent material (for example the cladding itself) fills the gap 17. In this architecture the height of the pattern 16' can be larger. If the relative refractive index difference between the filled gap 17 and the pattern 16' is set to 4%, then the pattern height is set to 13 microns. This height is still smaller than the 'Rayleigh range'.

The width of the wavefront in a fiber is of the order of microns. Since modern photolithographic methods can achieved sub-micron resolution, photolithography can be used to create the desired pattern on the face of the fiber.

Just as photolithography makes it is possible to accurately etch or coat the desired pattern on the edge of the fiber, multiple lithographic processes make it possible to approximate any continuous pattern. Accurate alignment of the fiber core to the desired pattern can be achieved by illuminating the fiber through the core.

Another method for creating a pattern 16 on the end face of a fiber is to attach a short (i.e., a few tenths of microns in length) fiber having the desired pattern 16. It can also be done by attaching a long fiber to the fiber end face and cutting it to the desired length. This method is more convenient and less expensive in mass production.

An internally reflective spatial mode transformer 190 of the present invention is illustrated in FIG. 20a. The gaussian beam emerging from the end of a single mode fiber 186 includes a

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center portion 192 and an outer portion 194. The gaussian beam 192 and 194 enters the spatial mode transformer 190 where only the outer portion 194 is reflected from an internal surface 196 back into the center portion 192 so that the interference between the portions 192 and 194 results in a wavefront similar to that of the LP_{02} mode. The resulting wavefront passes through one or more lenses 198 which couple the wavefront into a high order mode fiber 188. The internal surface 196 can be made from a variety of reflectors including, but not limited to, metallic reflective materials and refractive index interfaces (e.g., a segment of optical fiber having a core-cladding interface). FIG. 20b illustrates an internally reflective spatial mode transformer 190 attached to the single mode fiber 186. In another embodiment shown in FIG. 13C, a fiber-based spatial mode transformer 190' is disposed between the ends of the two fibers 186 and 188. The mode transformer 190' includes a short segment of optical fiber with an expanded core 200 of high refractive index. The cores of the two fibers 186 and 188 can be expanded in order to improve the coupling efficiency between spatial modes.

The transverse transformation process is insensitive to the polarization of the propagating pulse. However, in many applications it is necessary to introduce different phase shifts to the different polarizations of the pulse. This can be desirable because the polarization of the LP_{01} mode in the single mode fiber can be different from that of the higher order modes such as the TE_{01} mode. FIG. 14 depicts an embodiment for such an application. In this embodiment a collimating lenses 88, a polarization beam splitter 92, and a combiner 96 are conventional bulk elements. Special mirrors 100 and 102 perform the transverse mode transformation. These mirrors 100 and 102 are designed to introduce phase changes to the reflected wavefronts. One way of achieving this is by etching patterns on the mirrors themselves. In another embodiment, the transverse mode transformer 28 is constructed as a single bulk component 109 as shown in FIG. 15. The incident optical beam 110 is split into two orthogonally polarized beams 111 and 113 by a polarization beam splitter 115. Each beam is then reflected by total internal reflection from sides 114, and recombined at polarization beam splitter 115 into a single output beam 112.

The effect of this element 109 on the polarization of the light passing through it is illustrated in FIG. 16. An arbitrarily polarized pulse 120 is split to its two orthogonal polarization components 124a and 124b by the polarization splitter 115. The phase of each component 124a and 124b is changed by the phase elements on the mirrors 114 resulting in altered components 128a and 128b. A polarization beamsplitter 115 combines the components 128a and 128b into a

single annular distribution 132. The orientation of the phase elements on the mirrors 114 which are used to generate the altered components 128a and 128b can be rotated so that all LP_{11} modes can be generated separately. As a result, only a single mode propagates in the fiber 84. One advantage is that a polarization-maintaining fiber is not required.

If the polarization of the incident pulse is known (after a polarizer or a polarizing splitter) then it is possible to transform its polarization to match that of the high order modes in the fiber. This polarization transformation can be done with a fine transverse grating. For example, the polarization of the LP_{01} mode (the lowest order mode), which is basically linear and uniform across the mode, can be transformed to an azimuthal one (as that of the TE_{01}) by using a transverse grating with a varying local period.

Alternatively, a birefringent element can be used. FIG. 17 represents a physical description of the process of transforming a linear polarization towards angular polarization by using a retardation plate. The linear polarization 140 passes through a waveplate having primary axes oriented at an angle to the orientation of the linear polarization 142. The height of the plate is designed to have an angular dependence according to the equation $H_1(r,\theta)= D/(2\pi)\theta$, where D is defined as the depth for which the birefringence waveplate is not changing the orientation of linear polarization. The resulting polarization 144 is shown in FIG. 17. However, this wavefront may have a residual angular phase. Therefore, another non-birefringent element 146 is used to compensate for any residual angular phase. This element introduces the negative angular phase. This phase can be presented as $H_2(r,\theta)=-F/(27\pi)\theta$, where F is calculated according to the residual angular phase. The same effect can be achieved also by using two retardation waveplates having opposite angular phases and their primary axis oriented at opposite angles to the linear polarization.

The transverse phase elements can be implemented in a few configurations according to the requirements of the complete system. FIG. 18 represents a conventional system designed to eliminate the sensitivity of the system to polarization mode dispersion. The light propagating in a single mode fiber 3 enters a circulator 160 or a coupler (not shown). Then the light passes through the transverse mode transformer 162. The light is propagated as a higher order mode in the dispersion compensation fiber 164. A Faraday mirror 166 then reflects the light. After the light has passed again through the dispersion compensation fiber 164 and transverse mode

transformer 162, the circulator 160 separates the outgoing light for propagation through fiber 3' from the incoming light propagating through fiber 3.

However, in many applications circulators 160 are not desired because of their expense and complexity. Couplers (i.e., beamsplitters) are also undesirable because they introduce an inherent 50% loss. FIG. 19 represents a configuration in which a circulator or coupler is not needed. The light is separated into its orthogonal polarizations by the polarization splitter 172. Then, each polarization passes through a Faraday rotator 174 imparting a 45° polarization rotation to the polarization and then through a phase element 178. A polarization conserving special fiber 180 or an elliptical special fiber 180 is oriented at 45° so it is parallel to the transmitted polarization. The influence of the two Faraday rotators 174 cancels the rotation introduced by the special fiber 180. As a result, the two polarizations return to their original state and are combined at the polarizer 172 in the same orientation. As the two polarizations are counter-propagating in the special fiber 180, they have the same orientation. Therefore, they will be combined without time difference.

Thus, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense. It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention described herein.

Claims

We claim:

1. A chromatic dispersion compensation module comprising:

a first chromatic dispersion compensation fiber comprising a first end and a second end;

a second chromatic dispersion compensation fiber comprising a first end and a second end, said first end of said second chromatic dispersion compensation fiber optically coupled to said second end of said first chromatic dispersion compensation fiber; and

a first transmission fiber optically coupled to said first end of said first chromatic dispersion compensation fiber,

wherein light entering said first chromatic dispersion compensation fiber from said first transmission fiber is chromatic dispersion compensated by said first chromatic dispersion compensation fiber, and

wherein light entering said second chromatic dispersion compensation fiber from said first chromatic dispersion compensation fiber is further dispersion compensated by said second chromatic dispersion compensation fiber.

2. A chromatic dispersion compensation module comprising:

a plurality of chromatic dispersion compensation fibers each having a first end and a second end and each having a plurality of dispersion orders,

wherein the plurality of dispersion orders is different for each of said chromatic dispersion compensation fibers,

wherein each fiber of said plurality of chromatic dispersion compensation fibers is optically coupled to at least one other of said plurality of chromatic dispersion compensation fibers and

whereby the effect on an optical signal of a plurality of dispersion orders is modified.

3. The optical communication system of claim 1 wherein said first spatial mode is of a different order than said second spatial mode.

4. The optical communication system of claim 1 wherein said high order mode fiber propagates the LP_{02} spatial mode.

5. An optical communication system comprising:

a high order mode fiber having an optical output port; and

a transverse mode transformer optically coupled to said optical output port of said high order mode fiber,

wherein said transverse mode transformer transforms an optical signal exiting said high order mode fiber and having a first spatial mode to an optical signal having a second spatial mode.

6. The optical communication system of claim 5 wherein said high order mode fiber is a chromatic dispersion compensation fiber.

7. The optical communication system of claim 5 wherein said first spatial mode is of a different order than said second spatial mode.

8. The optical communication system of claim 5 wherein said high order mode fiber propagates the LP_{02} spatial mode.

9. An optical communication system comprising:

a high order mode fiber comprising a first end and a second end;

a first transverse mode transformer optically coupled to said first end of said high order mode fiber; and

a second transverse mode transformer optically coupled to said second end of said high order mode fiber;

wherein said first transverse mode transformer transforms an optical signal having a first spatial mode to an optical signal having a second spatial mode prior to being injected into said high order mode fiber,

wherein light from said high order mode fiber is transformed from said optical signal having a second spatial mode to an optical signal having a third spatial mode using said second transverse mode transformer.

10. The optical communication system of claim 9 wherein said high order mode fiber is a chromatic dispersion compensation fiber.

11. The optical communication system of claim 9 wherein said high order mode fiber has a length and a chromatic dispersion sufficient to substantially compensate for the chromatic dispersion of an optical signal entering the first transverse mode transformer.

12. The optical communication system of claim 9 wherein said first spatial mode and said third spatial mode are the same.

13. The optical communication system of claim 9 wherein said first spatial mode is of a different order than said second spatial mode.

14. The optical communication system of claim 9 wherein said high order mode fiber propagates the LP_{02} spatial mode.

15. The optical communication system of claim 9 further comprising a transmission fiber optically coupled to said first transverse mode transformer.

16. The optical communication system of claim 9 further comprising a transmission fiber optically coupled to said second transverse mode transformer.

17. The optical communication system of claim 9 further comprising an optical detector optically coupled to said second transverse mode transformer.

18. The optical communication system of claim 9 further comprising an optical source optically coupled to said first transverse mode transformer.

19. An optical communication system comprising:

a high order mode fiber having a first end and a second end;

a first transverse mode transformer optically coupled to said first end of said high order mode fiber;

a second transverse mode transformer optically coupled to said second end of said high order mode fiber;

a first transmission fiber optically coupled to said first transverse mode transformer; and

a second transmission fiber optically coupled to said second transverse mode transformer;

wherein an optical signal having a lower order spatial mode from said first transmission fiber is transformed by said first transverse mode transformer to an optical signal having a higher order spatial mode prior to being injected into said high order mode fiber,

wherein light from said high order mode fiber is transformed from said optical signal having a higher order spatial mode to an optical signal having a lower order spatial mode after exiting said high order mode fiber.

20. The optical communication system of claim 19 wherein said high order mode fiber is a chromatic dispersion compensation fiber.

21. The optical communication system of claim 19 wherein said first transmission fiber and said second transmission fiber are single mode fibers.

22. The optical communication system of claim 19 wherein said high order mode fiber propagates the LP_{02} spatial mode.

23. A method for compensating for chromatic dispersion in an optical communication system comprising the steps of:

a) receiving an optical signal having a first spatial mode;

b) spatially transforming said optical signal having a first spatial mode to an optical signal having a second spatial mode; and

c) dispersion compensating said optical signal having said second spatial mode.

24. The method of claim 23 wherein said first spatial mode is of a different order than said second spatial mode.

25. The method of claim 23 further comprising the step of providing a first transverse mode transformer wherein said first transverse mode transformer transforms said optical signal having said first spatial mode to said second spatial mode.

26. The method of claim 23 wherein said first spatial mode is of a different order than said second spatial mode.

27. A method for compensating for chromatic dispersion in an optical communication system comprising the steps of:

a) receiving an optical signal having a first spatial mode;

b) dispersion compensating said optical signal having said first spatial mode; and

c) spatially transforming said optical signal having said first spatial mode to a second spatial mode.

28. The method of claim 27 wherein said first spatial mode is of a different order than said second spatial mode.

29. A method for compensating for chromatic dispersion in an optical communication system comprising the steps of:

a) receiving an optical signal having a first spatial mode;

b) spatially transforming said optical signal to an optical signal having a second spatial mode;

c) dispersion compensating said optical signal having said second spatial mode; and

d) spatially transforming said optical signal having said second spatial mode to an optical signal having a third spatial mode.

30. The method of claim 31 wherein said first spatial mode and said third spatial mode are the same.

31. The method of claim 31 wherein said first spatial mode is of a different order than said second spatial mode.

32. The method of claim 31 further comprising the step of providing a first transverse mode transformer wherein said first transverse mode transformer transforms said optical signal having said first spatial mode to said optical signal having said second spatial mode..

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33. The method of claim 31 further comprising the step of providing a second transverse mode transformer wherein said second transverse mode transformer transforms said optical signal having said second spatial mode to said optical signal having said third spatial mode.

34. The method of claim 31 wherein said second spatial mode is of a different order than said third spatial mode.

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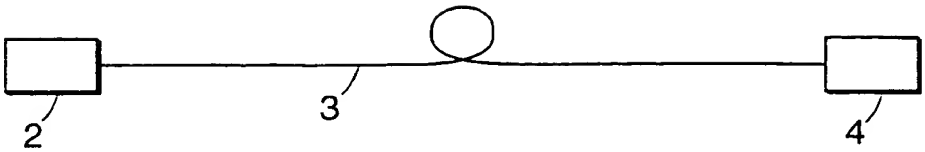

FIG. 1
PRIOR ART

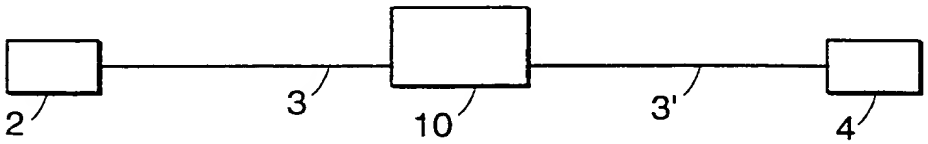

FIG. 2

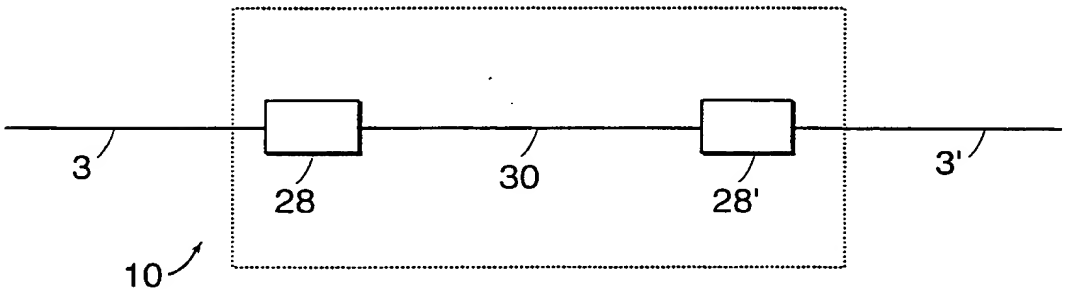

FIG. 3
PRIOR ART

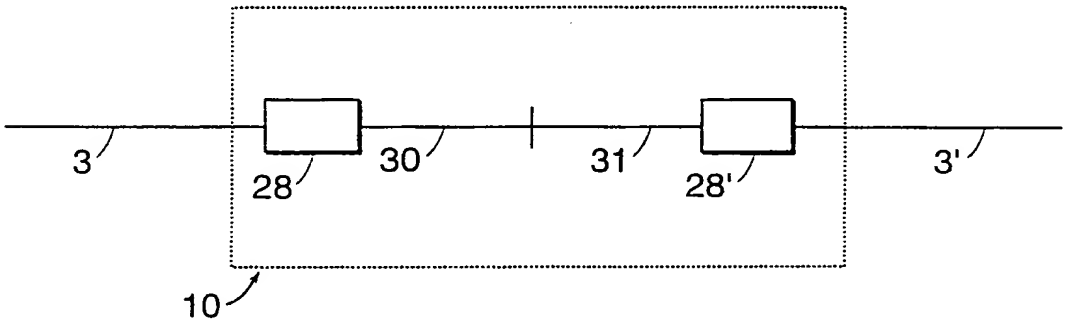

FIG. 4
PRIOR ART

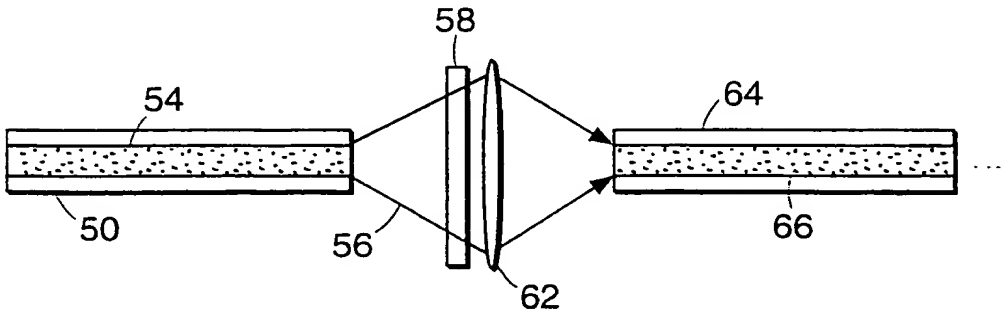

FIG. 5

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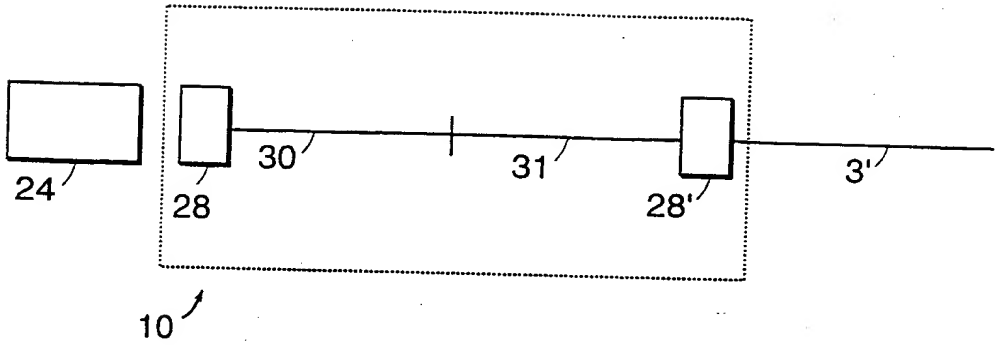

FIG. 6A

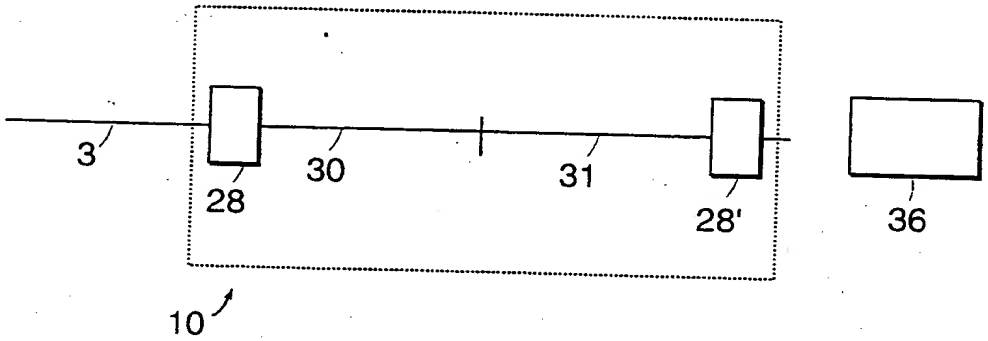

FIG. 6B

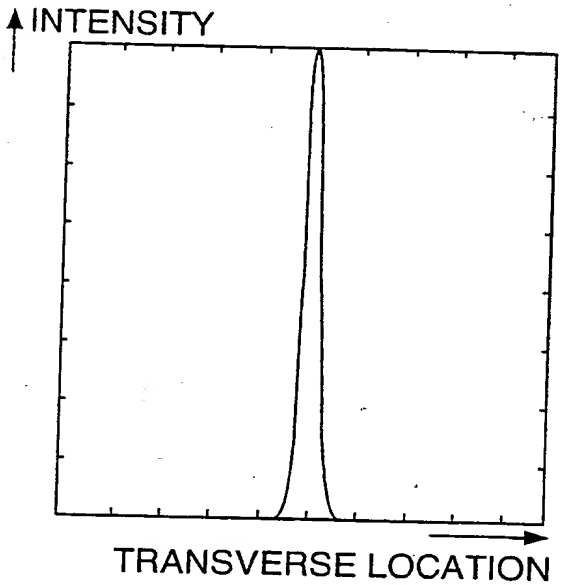

FIG. 7A

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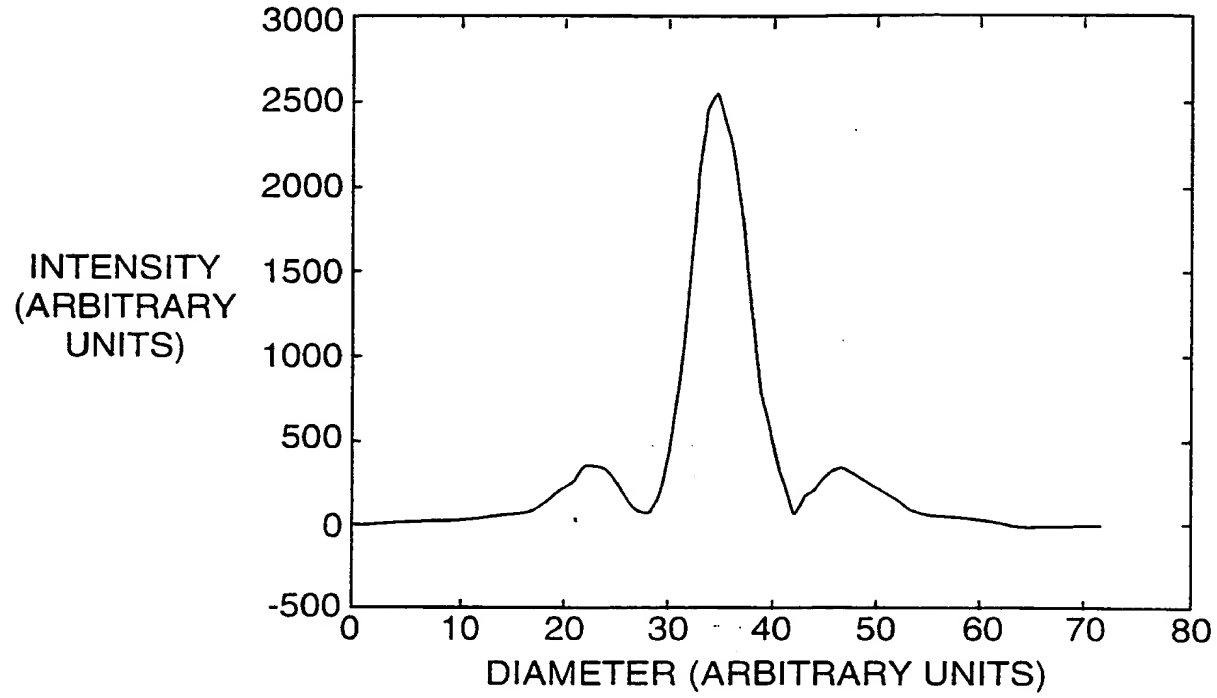

FIG. 7B

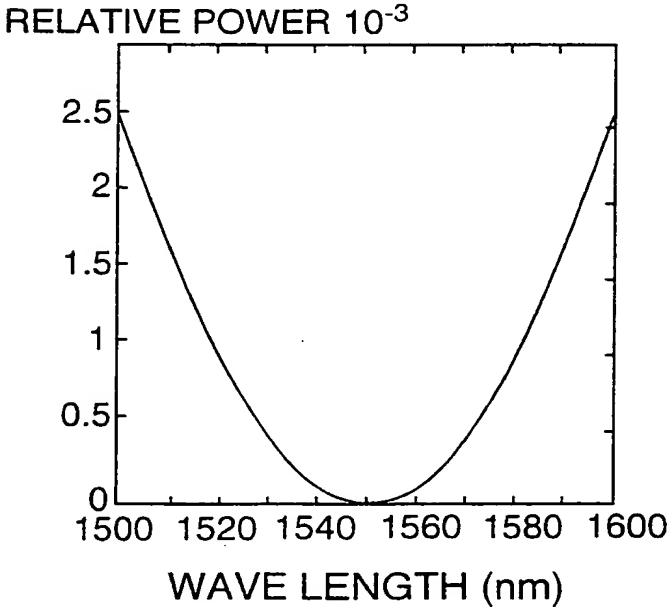

FIG. 8

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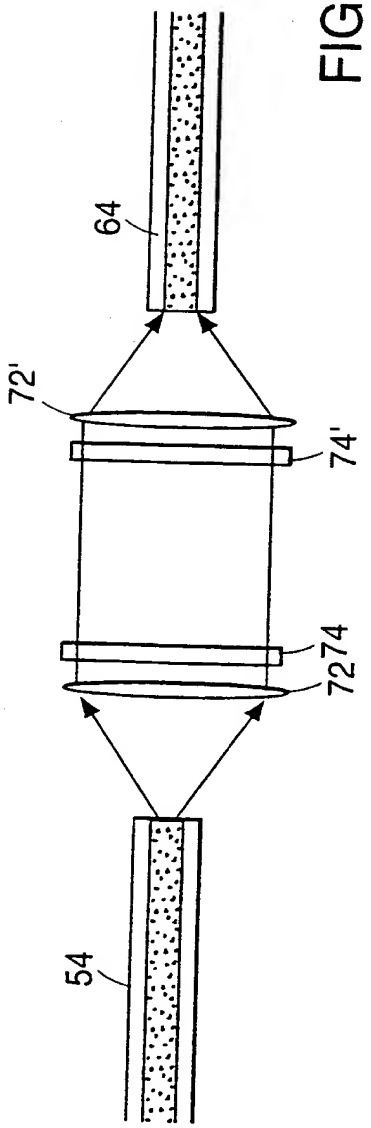

FIG. 9

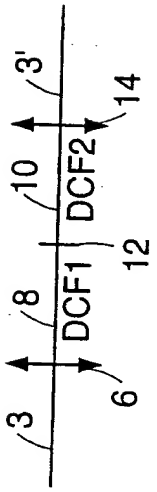

FIG. 10A

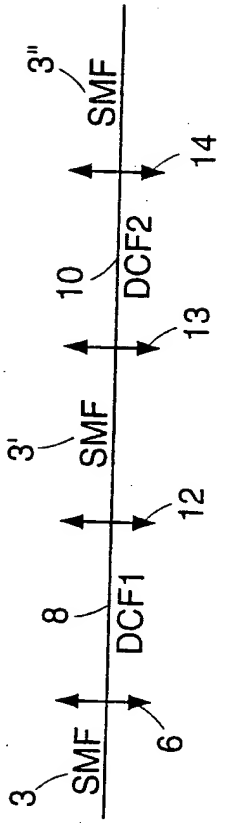

FIG. 10B

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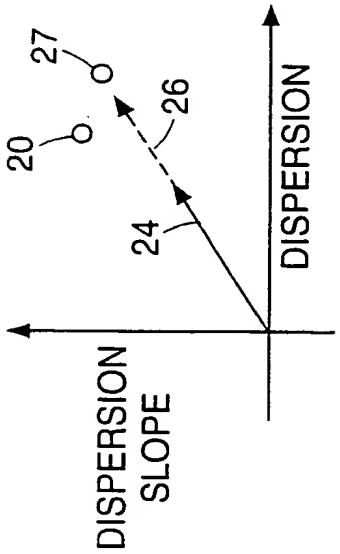

FIG. 11B

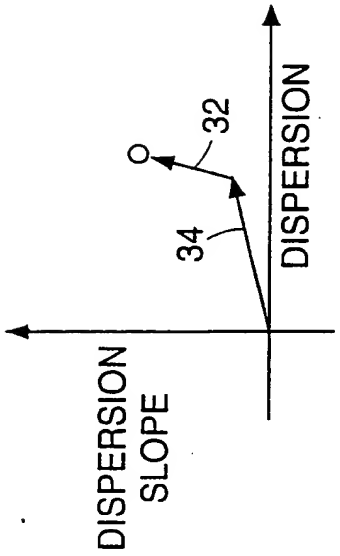

FIG. 11D

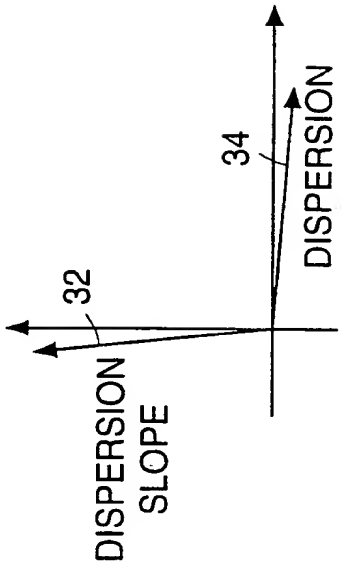

FIG. 11E

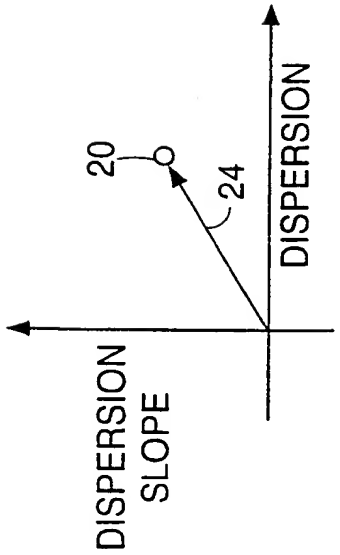

FIG. 11A

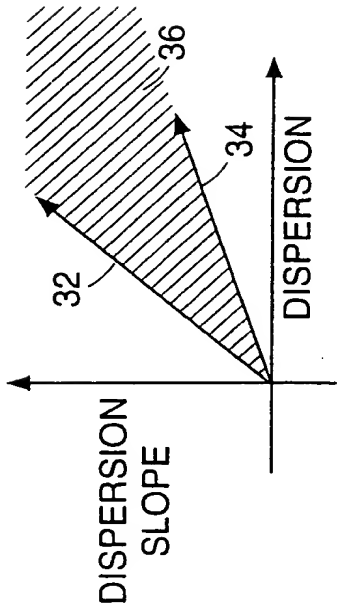

FIG. 11C

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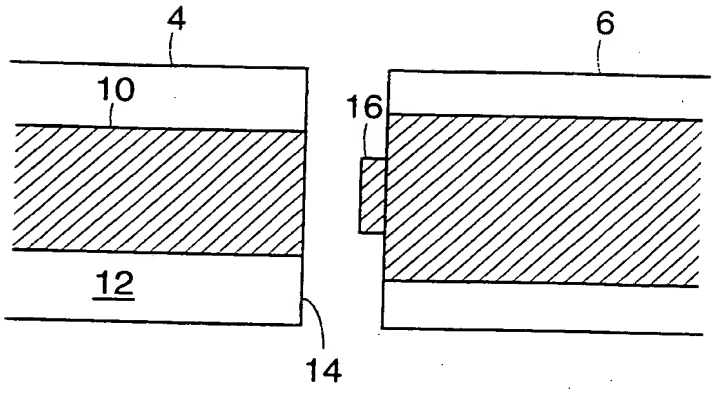

FIG. 12A

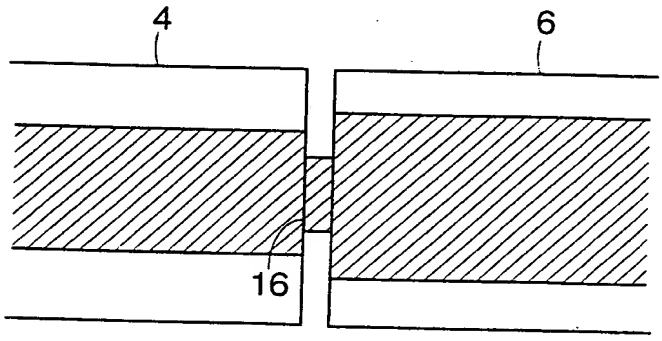

FIG. 12B

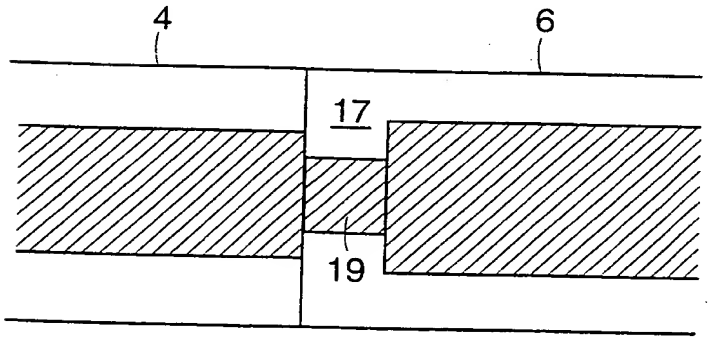

FIG. 12C

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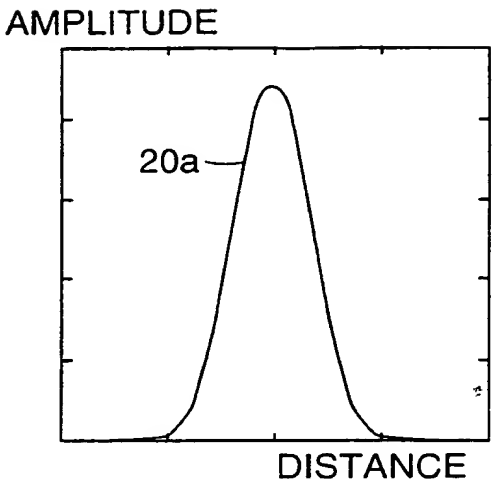

FIG. 13A

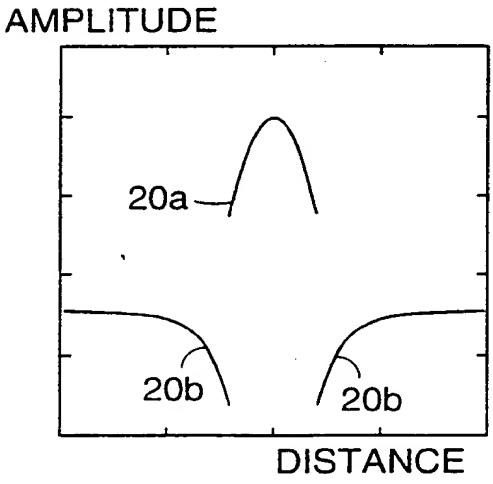

FIG. 13B

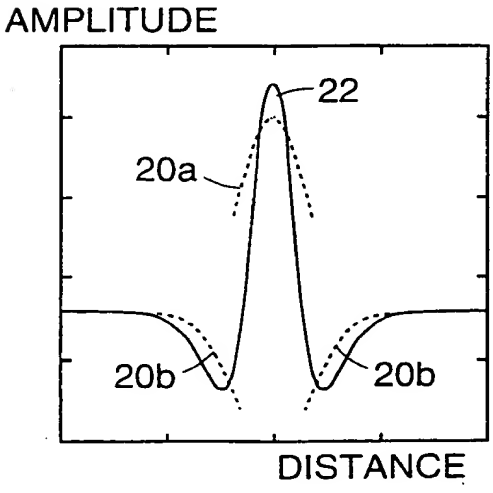

FIG. 13C

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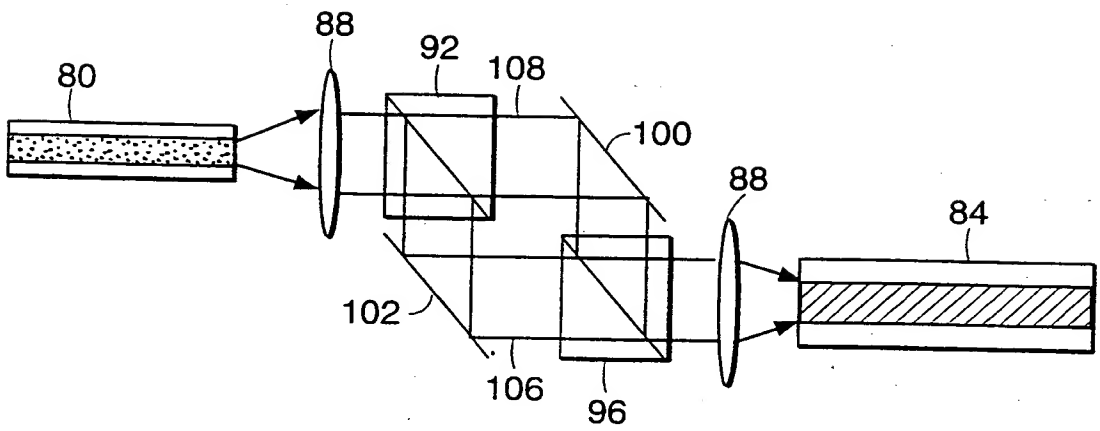

FIG. 14

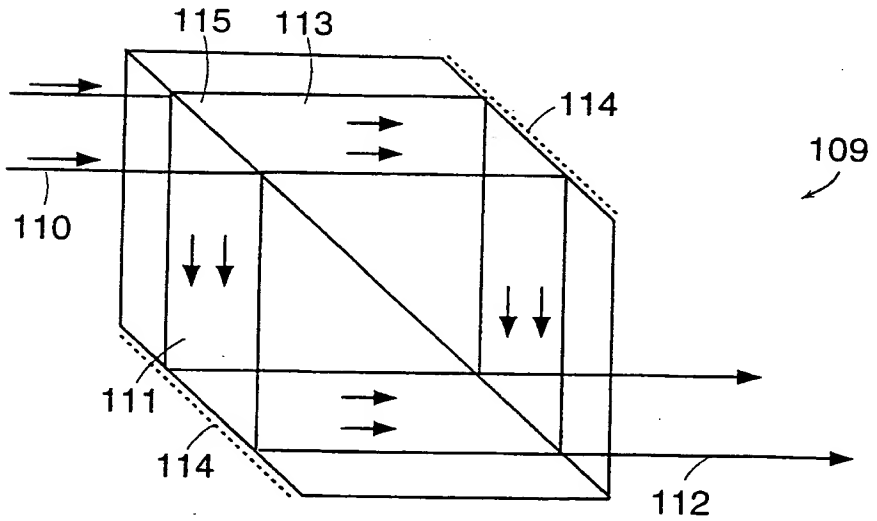

FIG. 15

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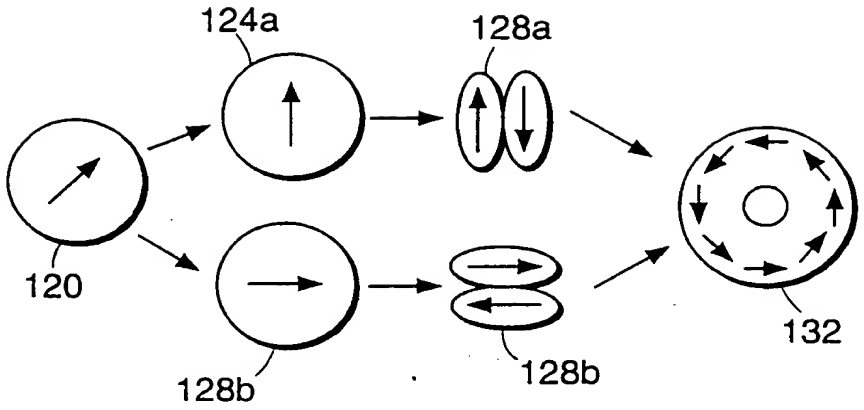

FIG. 16

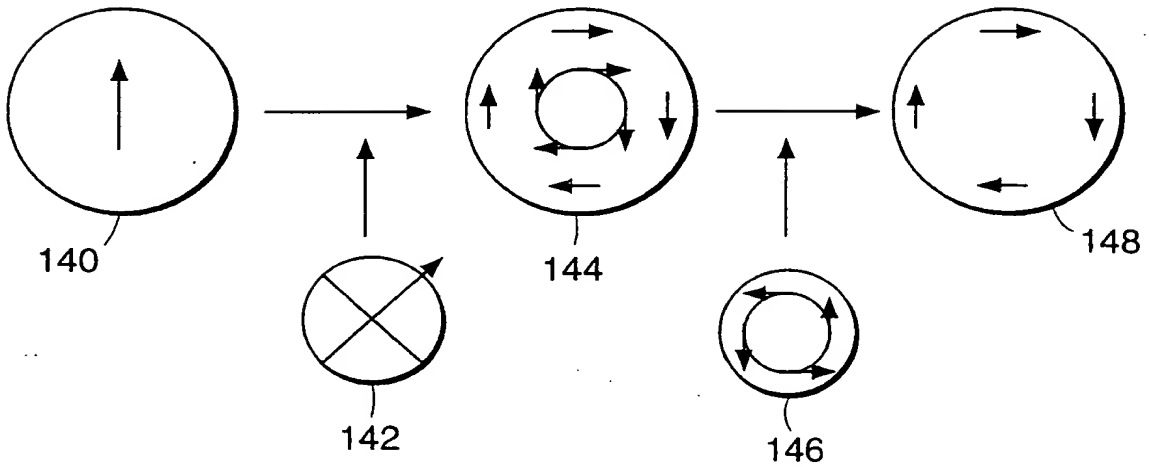

FIG. 17

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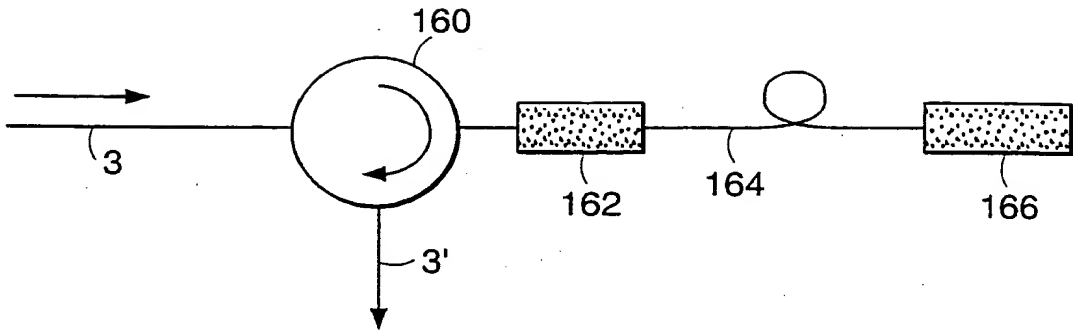

FIG. 18

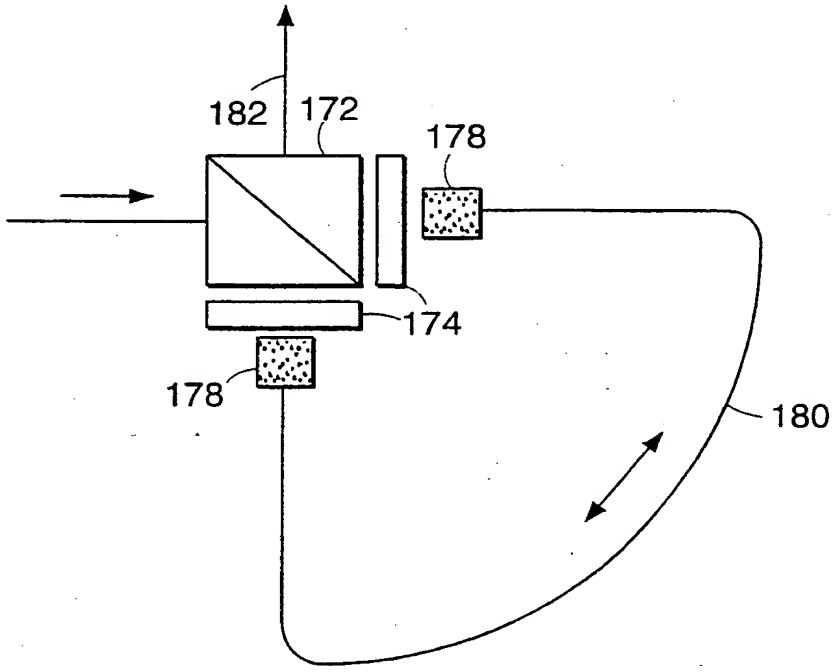

FIG. 19

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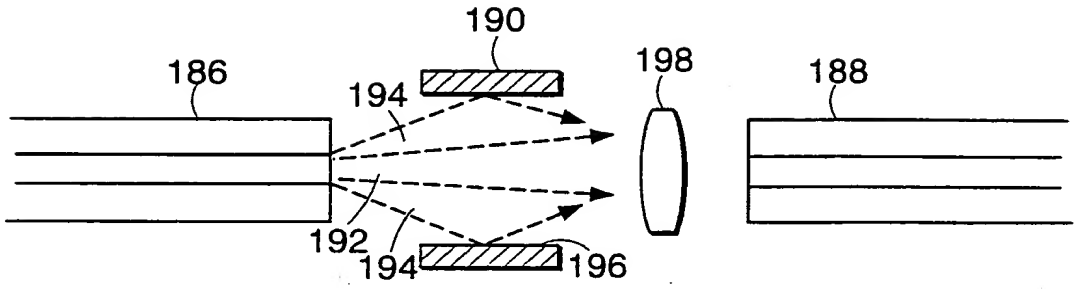

FIG. 20A

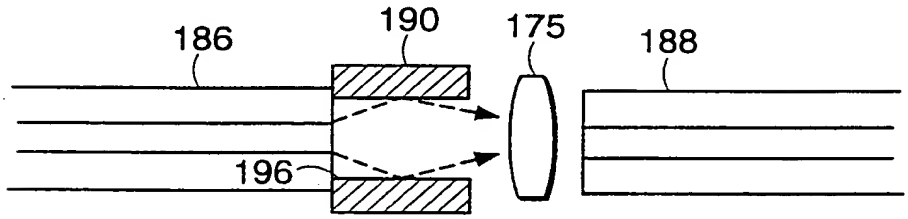

FIG. 20B

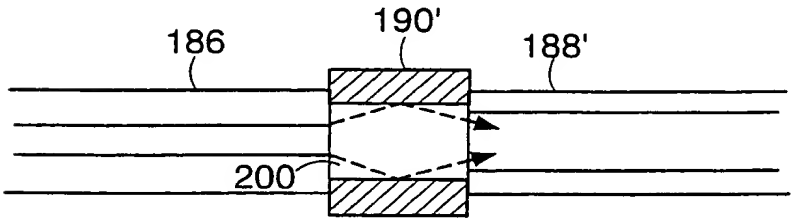

FIG. 20C

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(74) Agent: GUERIN, William, G.; Testa, Hurwitz & Thibeault, LLP, High Street Tower, 125 High Street, Boston, MA 02110 (US).

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(54) Title: APPARATUS AND METHOD FOR COMPENSATION OF CHROMATIC DISPERSION IN OPTICAL FIBERS

(57) Abstract

A dispersion compensation device uses at least two chromatic dispersion compensation fibers to compensate for chromatic dispersion present in an optical communication system. Two dispersion orders can be corrected using appropriate lengths of two serially coupled compensation fibers having different dispersion characteristics. The device can compensate for N additional orders of dispersion by using N additional compensation fibers with unique dispersion characteristics. The device can be coupled directly to a transmission fiber.

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CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

BNSDOCID: <WO___9949340A3_I_>

INTERNATIONAL SEARCH REPORT

International Application No
Pc./US 99/06479

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B10/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04B G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 097, no. 010, 31 October 1997 (1997-10-31) & JP 09 167995 A (KOKUSAI DENSHIN DENWA CO LTD <KDD>), 24 June 1997 (1997-06-24) abstract; figure	1
A		2

X	EP 0 590 633 A (SUMITOMO ELECTRIC INDUSTRIES) 6 April 1994 (1994-04-06) abstract; figure 13 column 2, line 14 - line 20 column 2, line 45 - line 54 column 8, line 55 -column 9, line 14	1
A		2

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
5 October 1999	11.10.1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hylla, W

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BNSDOCID: <WO___9949340A3_I_>

INTERNATIONAL SEARCH REPORT

International Application No
PC./US 99/06479

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 594 344 A (AMERICAN TELEPHONE & TELEGRAPH) 27 April 1994 (1994-04-27) claims 1,6,7; figure 1	1,2
X	DE 24 33 153 A (SIEMENS AG) 29 January 1976 (1976-01-29)	5,23,25, 27
A	page 1, paragraph 2 - paragraph 5 page 3, paragraph 1; claim 1; figures 1,2	9,19,29
Y	US 5 261 016 A (POOLE CRAIG D) 9 November 1993 (1993-11-09) abstract; figures 1,11 column 3, line 18 - line 43 column 4, line 52 -column 5, line 14	5,9,19, 23,27,29
Y	US 5 448 674 A (VENGSARKAR ASHISH M ET	
A	AL) 5 September 1995 (1995-09-05) abstract; figure 3 column 2, line 65 -column 3, line 40 column 5, line 16 - line 30	5,9,19, 23,27,29 6-8,10, 13,14, 20-22
A	GOEL A ET AL: "WIDE-BAND DISPERSION COMPENSATINGOPTICAL FIBER" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 8, no. 12, 1 December 1996 (1996-12-01), pages 1668-1670, XP000679544 ISSN: 1041-1135 abstract; figure 1 page 1669, left-hand column, paragraph 2 page 1670, right-hand column, paragraph 1	5,9,19, 23,27,29
A	POOLE C D ET AL: "OPTICAL FIBER-BASED DISPERSION COMPENSATION USING HIGHER ORDER MODES NEAR CUTOFF" JOURNAL OF LIGHTWAVE TECHNOLOGY, vol. 12, no. 10, 1 October 1994 (1994-10-01), pages 1746-1758, XP000469528 ISSN: 0733-8724	9,19,23, 27,29

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

BNSDOCID: <WO___9949340A3_I_>

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 99/06479

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☒ No protest accompanied the payment of additional search fees.

BNSDOCID: <WO___9949340A3_I_>

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-4

   Chromatic dispersion compensating module characterised by using a plurality of chromatic dispersion compensating fibers coupled to one another

2. Claims: 5-34

   Optical communication system characterised by using a high order mode fiber and a transverse mode transformer and method for compensating chromatic dispersion in such a system

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INTERNATIONAL SEARCH REPORT

.nformation on patent family members

Int· ·ıtional Application No
PC·/US 99/06479

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JP 09167995 A	24-06-1997	NONE	
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